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March 5, 2012

The XIX International Conference on Computational Methods
in Water Resources
Urbana, IL, United States
June 17, 2012 through June 22, 2012

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A THREE-DIMENSIONAL GAS MIGRATION MODEL FOR THE LEROY NATURAL GAS-STORAGE FACILITY

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Key words: Aquifer gas-storage reservoir, gas migration, caprock seal, fault, wellbore leakage

Abstract. Gas loss from an aquifer gas-storage reservoir can occur through a number of potential pathways, including faults, an incomplete caprock seal, or boreholes. In this paper, we develop a 3-D gas migration model built on a realistic site-specific hydrogeologic model of the aquifer gas-storage reservoir at the Leroy natural gas-storage facility, which experienced uncontrolled gas leakage in the 1970's. The 3-D model was validated by field pressure and inventory data. The simulated methane distribution was analyzed to evaluate the leakage pathway. Predicted pressure was used to drive a geomechanical stability analysis of the bounding fault. Our results indicate that fault leakage remains an open possibility, though several unexplained observations remain and other counter-hypotheses are still being considered.

1 INTRODUCTION

Underground natural gas storage plays a vital role in maintaining consistent delivery to meet the seasonal consumer demands. Greater than 13% of annual natural gas consumption (3.1 trillion cubic feet) is delivered from over 400 storage reservoirs across the United States. Future consumption of natural gas is projected to increase by 1.4% per year¹. There will be a significant need for continuing development of large-scale gas-storage reservoirs, as well as maintaining the current ones. For any gas-storage reservoir, gas leakage is a critical concern, both economically and environmentally. Possible leakage pathways include poorly completed wells, geologic faults, or failed caprock seals². Relatively few gas-leakage analyses have been published for underground natural gas storage, although a number of recent studies have addressed leakage concerns of CO₂ geologic storage, with some using reduced-order analytical models³, and others using two-dimensional numerical models of simplified hydrogeologic domains⁴. However, the leakage rate, as well as its spatial and temporal distribution, can critically depend on the details of the hydrogeology, as well as coupled hydro-mechanical processes involved in the injection, storage, and extraction of natural gas in the deep aquifer, including fluid pressurization, phase displacement, component dissolution, and permeability and porosity changes⁵. It may also cause injection-induced seismicity and reactivation of pre-existing faults. To accurately simulate gas leakage for a realistic storage facility, three-dimensional models capable of simulating these processes must be built on a site-specific hydrogeological domain. In this study, we developed a

realistic three-dimensional gas migration model for the Leroy natural gas-storage facility, which is unique because of the documented period of gas leakage from the reservoir to the surface over thirty years ago. The objective of this study is to use the Leroy gas-storage site to (1) investigate the hydrogeologic and geomechanical state of the reservoir during gas injection and extraction, (2) analyze the possible leakage pathways.

2 LEROY GAS-STORAGE FACILITY

The Leroy natural gas-storage facility is an aquifer gas-storage reservoir developed in Uinta County, Wyoming, approximately 160 km northeast of Salt Lake City. The reservoir is an anticline bounded on its west side by a fault. The natural gas is injected into and extracted from the T-10 zone, a highly permeable sandstone aquifer at the depth of about 900 m in the lower Thaynes Formation. The upper and middle Thaynes Formation contains red shale, siltstone, and forms the caprock seal. Following discovery of gas leaking from the reservoir in 1978, the operator of the storage facility, Questar Pipeline, reduced the maximum operating pressure of the reservoir to a level which resolved the problem after 1982. In this study we focus on evaluating the leakage through faults using the developed model, although several alternative leakage-pathway hypotheses remain possible.

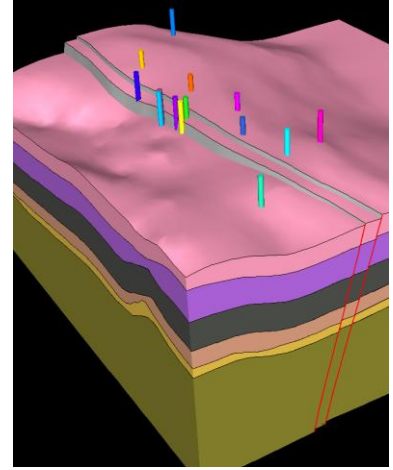


Figure 1: Earthvision geological model for Leroy storage site

3 MODEL DEVELOPMENT

3.1 Earthvision cellular grid

A 3-D faulted geological model of the Leroy gas-storage reservoir was constructed using Earthvision⁶. The stratigraphic layers are defined by the borehole logs scattered throughout the field. Interpretive structural contour maps of some of the horizons were made available by Questar Pipeline, and these data are used to constrain the geometry of the section. Plan maps of the fault traces were digitized and used for construction of the fault planes. A structural dip of 70 degrees was assigned to the faults (Figure 1).

Using an Earthvision meshing module (EVCELL), the geological structure model is transformed to a cellular grid consisting of irregularly shaped cells arrayed in I, J, and K dimension originated from the northwest corner (Figure 2). The domain cropped from the initial structure model is 3200,

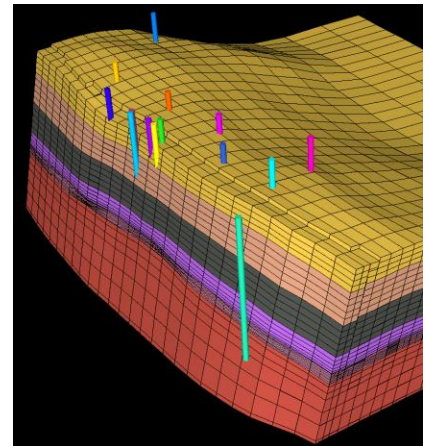


Figure 2: EVCELL grid for Leroy storage site

3600, and 2000 m in I, J, and K dimension respectively, bounded on the west by the fault, on top by the topographic surface, and at the base by bedrock. The cell size in I dimension increases from west to east since all of the wells are clustered in the west part of the domain along the major fault. The vertical cell size varies in different geological zones based on the mean thickness and importance of that zone, as shown in Table 1.

Layer formation	Material	Thickness (m)	NZ	DZ (m)	Permeability (m^2)	Por.	Res. Sat.
Topo	Overburden	240	6	60	12.5×10^{-14}	0.2	0.3
Twin creek	Limestone	150	4	38	1.0×10^{-16}	0.1	0.3
Nugget	Sandstone	225	5	45	1.0×10^{-14}	0.2	0.3
Ankareh	Caprock	230	5	46	1.0×10^{-17}	0.1	0.3
Thaynes	Caprock	130	6	22	1.0×10^{-17}	0.1	0.3
T-10	Storage	80	10	8	1.76×10^{-13}	0.138	0.2
Woodside	Bedrock	500	7	70	1.0×10^{-17}	0.1	0.3
Fault	-	-	-	-	1.0×10^{-13}	0.3	0.01

Table 1: Geometry and hydrology of each geological formation.

3.2 Three-dimensional gas migration model

In this study, NUFT (Nonisothermal Unsaturated-saturated Flow and Transport), a code developed in Lawrence Livermore National Laboratory (LLNL), is used as a gas migration simulator^{7,8}. NUFT uses integral finite difference method for space discretization, where cell geometry properties, as well as neighboring connectivity, are necessary. An interface code converting EVCELL grids to NUFT-compatible external meshes was developed. Based on the cell geometry information including IJK index, coordinates, and size provided by EVCELL grid, neighboring cells are identified and their connectivity (distance, cross area, and connection angle) are calculated by using the interface tool.

The NUFT fluid flow and transport model is based upon the EVCELL grid of the realistic geological model of Leroy site. The hydrologic parameters for each

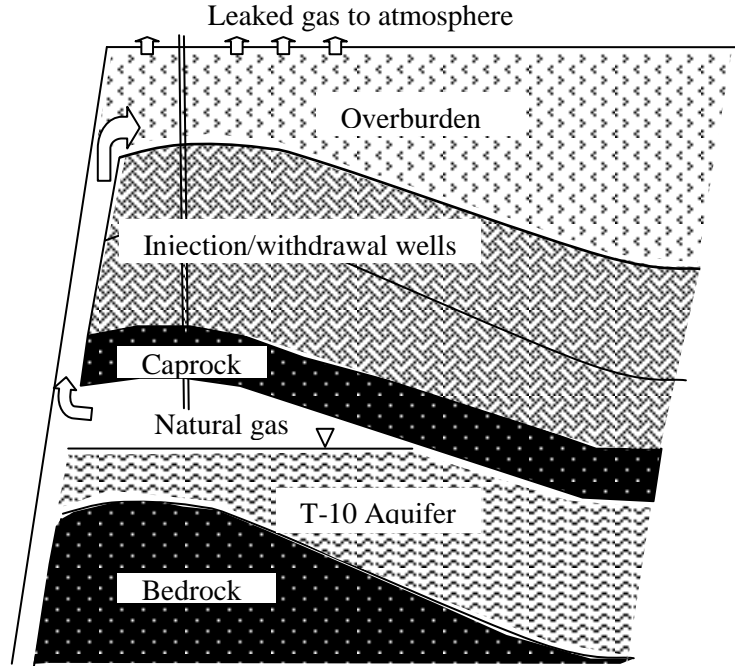


Figure 3: Cross-sectional view of the Leroy aquifer gas storage showing the gas migration through the fault.

geological zone are estimated from literature related to the Leroy site or obtained from the calibration of a simplified 2-D axisymmetric cylindrical model as listed in Table 1. A schematic representation of a vertical east-west cross section of the Leroy gas-storage site is shown in Figure 3. Boundary conditions at the land surface (2061 m elevation) are an atmosphere pressure of 7.8×10^4 Pa and a temperature of 8°C . A constant water infiltration of 292.8 mm/yr estimated from the averaged local monthly precipitation is also assigned to the top boundary. For an unsaturated-saturated flow system as in our study, the pressure on the bottom can usually be estimated from the groundwater level data, which is not available for the Leroy gas-storage site. However, the initial reservoir pressure (1.03×10^7 Pa) and temperature (27.7°C) are measured at a depth of 900 m⁹, from which we estimated pressure and temperature on the bottom boundary as 1.75×10^7 Pa and 33°C . As indicated above, the west side boundary is the fault zone and no flow inward or outward. The cell volume in east, north and south side boundary is magnified by a factor of one million to eliminate the boundary effect on gas and brine migration. Under these boundary conditions, the model simulates two-phase (gas, liquid), three-component (water, air, methane), thermal flow and transport in an unsaturated-saturated semi-infinite domain. We first run an initialization simulation for 1 million years to establish a steady-state flow system, from which the spatial distribution of gas pressure, temperature, liquid saturation, and component concentrations are obtained as the initial state of the reservoir before injection/withdrawal operation. Instead of putting source history on cells of perforation of 10 injection/withdrawal wells separately, we define an injection/withdrawal zone containing all the well perforations in T-10 storage aquifer, on which we distributed by volume the sum of source strength of all the wells (Figure 4). In this way, the stability of the numerical simulations is significantly improved with little influence on simulated storage pressure, leakage and inventory history, thanks to the highly permeable storage aquifer (permeability = 1.76×10^{-13} m²). This simplification is also justified by the results.

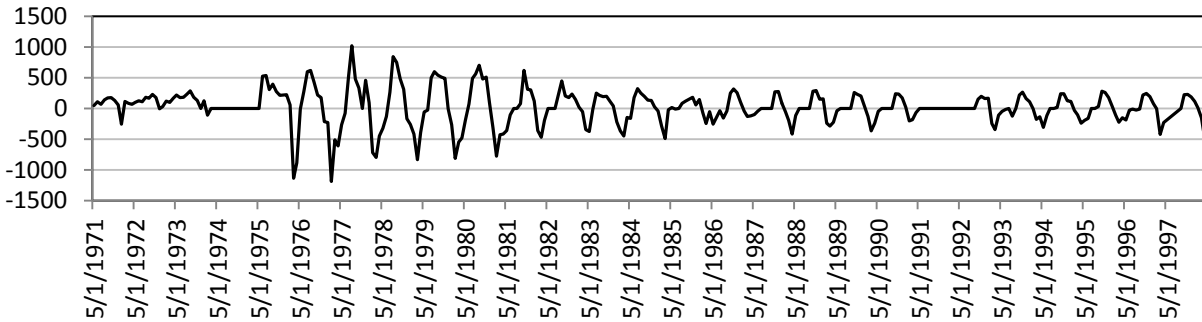


Figure 4: Monthly gas injection/withdrawal history summed over 10 wells (MMSCF). Positive values account for injection and negative means withdrawal. MMSCF stand for Million Standard Cubic Feet, a volume unit widely used in petroleum industry.

3.3 Geomechanical stability analysis

Using the simulated pressure history and geometry of the major bounding fault, we performed a preliminary fault stability analysis. The effective normal and tangential tractions acting at each

point on the fault were computed, and the potential for slip was estimated using a standard Coulomb slip criterion. Besides the pressure distribution acting on the fault, a key parameter for the analysis (and a key uncertainty) is the state of stress at depth. No site-specific data was available to constrain the stress magnitude and orientation at the Leroy gas-storage site, and so regional estimates were employed. Given their uncertain nature, these estimates have been used as baseline values within a preliminary uncertainty quantification analysis.

4 RESULTS AND DISCUSSION

4.1 Model validation

With the 27 years of injection/withdrawal data, the reservoir pressure and gas leakage to the ground surface are simulated by the 3-D gas migration model, and the inventory is calculated by subtracting leakage from the net injection. The simulated pressure history matches the measurement trend reasonably, and the inventory (leakage) matches the field data closely. This is especially clear after May, 1975, when the reservoir was fully developed and started to be operated in regular seasonal cycles (Figure 5), demonstrating the feasibility of the developed gas migration model.

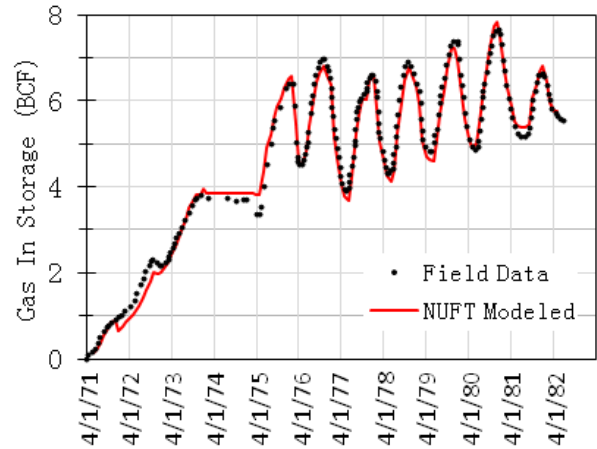


Figure 5: Comparison of simulated inventory against the field data. BCF stands for Billion Cubic Feet.

4.2 Leakage pathway analysis

The three-dimensional distribution of the methane fraction in the gas phase is a good indicator of how natural gas migrates in the system. April 1, 1975 is considered the breakthrough time to the surface, according to the simulated leakage history, as the plume edge almost reached the surface (Figure 6a). On 10/1/1975, when the reservoir pressure reached the peak during injection season, the plume extended horizontally on the ground surface. It is also noted that gas started to migrate from the fault zone to the permeable Nugget Formation overlying the caprock (Figure 6b). After three years of gas leakage (Figure 6c), most of the fault plane has become the pathway of upward gas migration, and the horizontal distribution of the plume at the surface roughly overlaps the detected gas footprint on November 1978¹⁰. A significant amount of methane migrated to the Nugget Formation from the fault zone horizontally by April 1982, the time when the gas leakage was controlled by limiting the maximum pressure (Figure 6d). The methane contained in Nugget Formation, in turn, can seep to the fault and then to the ground surface under some conditions, or through fractures across the overlying low-permeability Twin Creek Formation (permeability = 10^{-16} m²). In addition to the fault, fractures developing in the caprock during injection operations could provide another leakage pathway. According to field monitoring of surface bubbling, some bubbling corresponds to the timing of storage operations,

while some do not, indicating leakage originates not only directly from the storage zone, but also from intermediate collector zones. The possibility of gas collector zones existing in the Nugget Formation was ruled out in previous studies^{9,11}. It was argued that no collector zones can exist above the caprock since pressure did not increase in the observation well completed in the overlying formations. This argument is questionable, because (1) the well perforations may be located in low-permeability zones since the actual permeability is heterogeneous, even in the same geological layer. It is not reasonable to rule out permeable collector zones in a large geological layer based solely on observations from a single well. (2) Under hydrostatic pressure conditions above the caprock, buoyancy plays an important role for upward gas migration. (3) Barometric pumping may be strong enough to induce the vertical gas migration from the shallow collector zones to the ground surface, especially when faults or fractures exist^{12,13}.

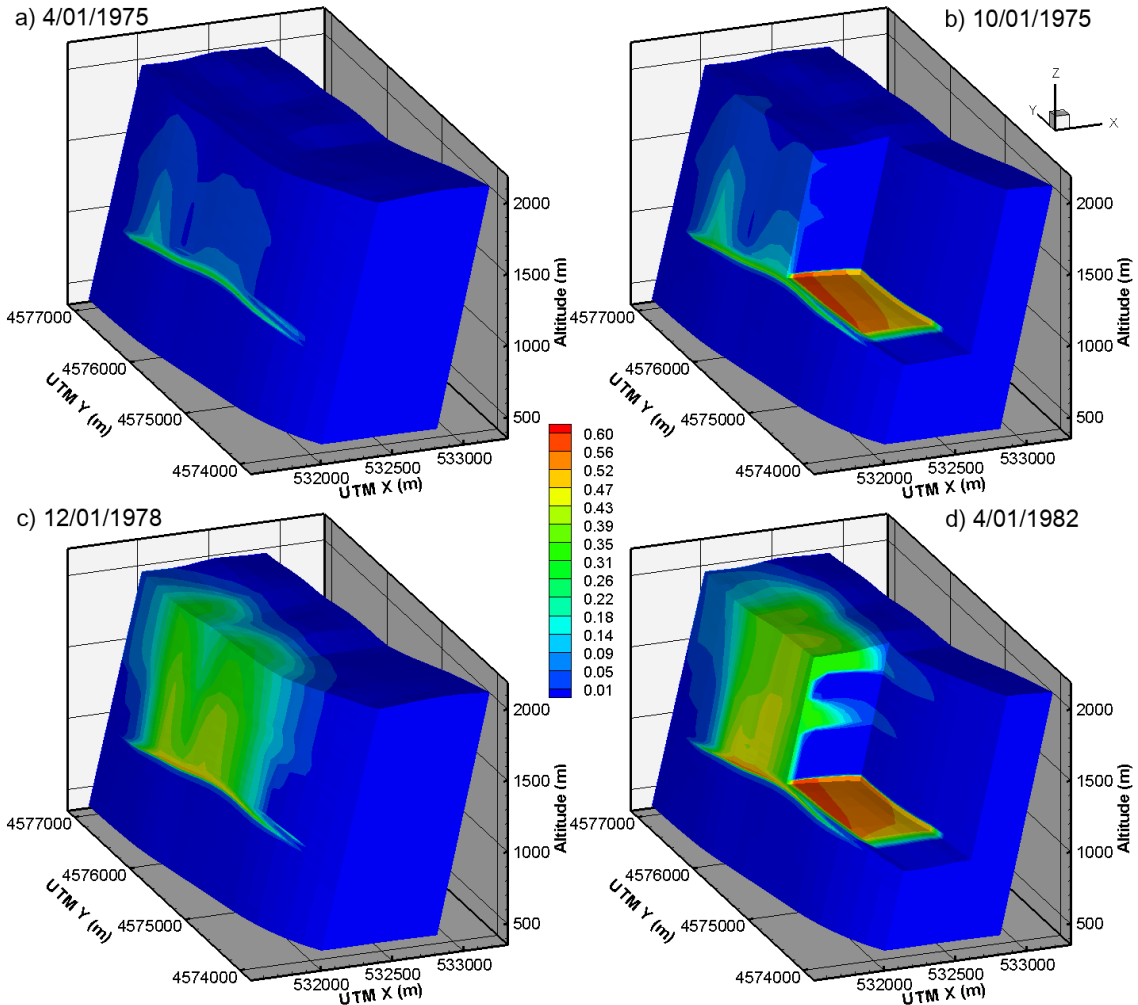


Figure 6: Three-dimensional contour of simulated mole fraction of Methane in gas phase on (a) 4/1/1975, (b) 10/1/1975, (c) 12/1/1978, and (d) 4/1/1982.

4.3 Stability analysis

Figure 7 plots the pressure at a sample point on the fault plane, as well as the estimated critical pressure required to induce slip. Also plotted is the minimum horizontal stress, which approximates the hydrofracturing pressure. The fault is well oriented for slip in the estimated regional stress field, but in this analysis it appears that the pressure on the fault never quite reaches the critical slip pressure and therefore remains stable. It should be noted though that small perturbation in the stress orientation and magnitude could lead to an unstable configuration. As a result, additional effort should be invested to constrain these sensitive parameters. Also, even in the absence of slip, a highly fractured zone around the fault might serve as a permeable pathway and exhibit a pressure-dependent response. One cannot therefore rule out the possibility of the fault leakage hypothesis based on a stability analysis alone.

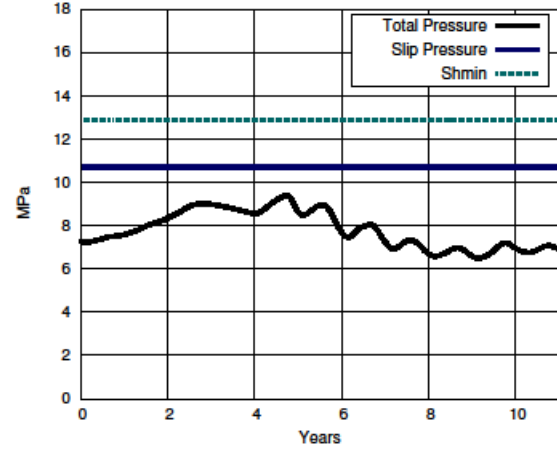


Figure 7: Pressure history on the fault and estimated critical slip pressure under the given assumptions.

5 CONCLUSION

A realistic, irregular, numerical mesh, honoring the fault and geological layer planes of the aquifer gas-storage reservoir in the Leroy natural gas-storage facility, is applied to a 3-D gas migration model. Based on the simulated spatial and temporal methane distributions, we conclude that during 1975-1982, it is plausible that natural gas leakage occurred through the fault from the T-10 aquifer gas-storage reservoir to the ground surface, as well as to the permeable Nugget Formation, overlying the caprock seal. Our results are consistent with field monitoring of surface bubbling, which suggest that both direct reservoir-to-surface leakage and indirect leakage from shallow collector zones in the Nugget Formation are possible. Although we demonstrate that gas leakage through the fault is a possible pathway, our analyses have not considered (and ruled out) alternative leakage pathways, including (1) the loss of caprock integrity, caused by a fracture network developing in the caprock seal units, and (2) wellbore leakage. Future work will examine these alternative leakage pathways, as well as the possibility of pressure-dependent fault permeability.

ACKNOWLEDGEMENTS

This work was sponsored by USDOE Fossil Energy, National Energy Technology Laboratory. The authors want to acknowledge and thank Questar Pipeline for furnishing technical information on the Leroy natural gas-storage facility. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.

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